NEUTRINO WORKING GROUP

André de Gouvêa, Kevin Pitts, Kate Scholberg, Sam Zeller

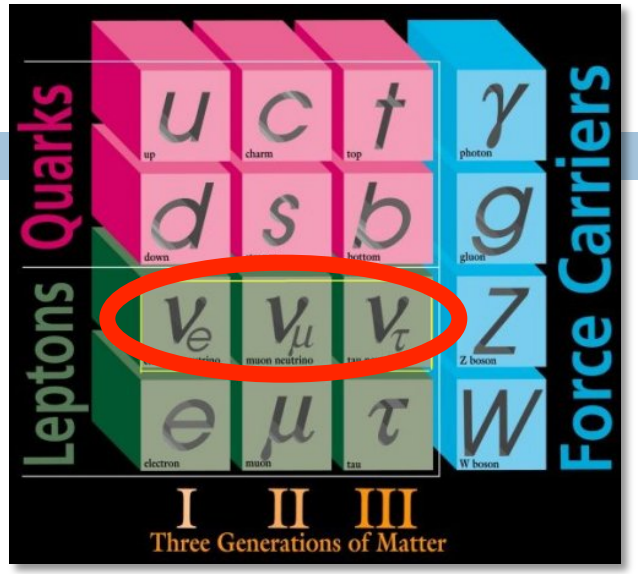
CPM at FNAL

October 12, 2012

- where we are after the IF report
  - highlight some updates since that report came out
- where do we go now?

http://if-neutrino.fnal.gov/

Big Questions in ν's



- we know that ν's oscillate and have seen evidence for this now in lots of ways
- but the picture is not complete and there are a lot of things we still don't understand:

- what is the neutrino mass ordering?

- do neutrinos violate CP?

- are neutrinos their own antiparticles?

- what are the masses of the neutrinos?

- are there more than 3 neutrinos?

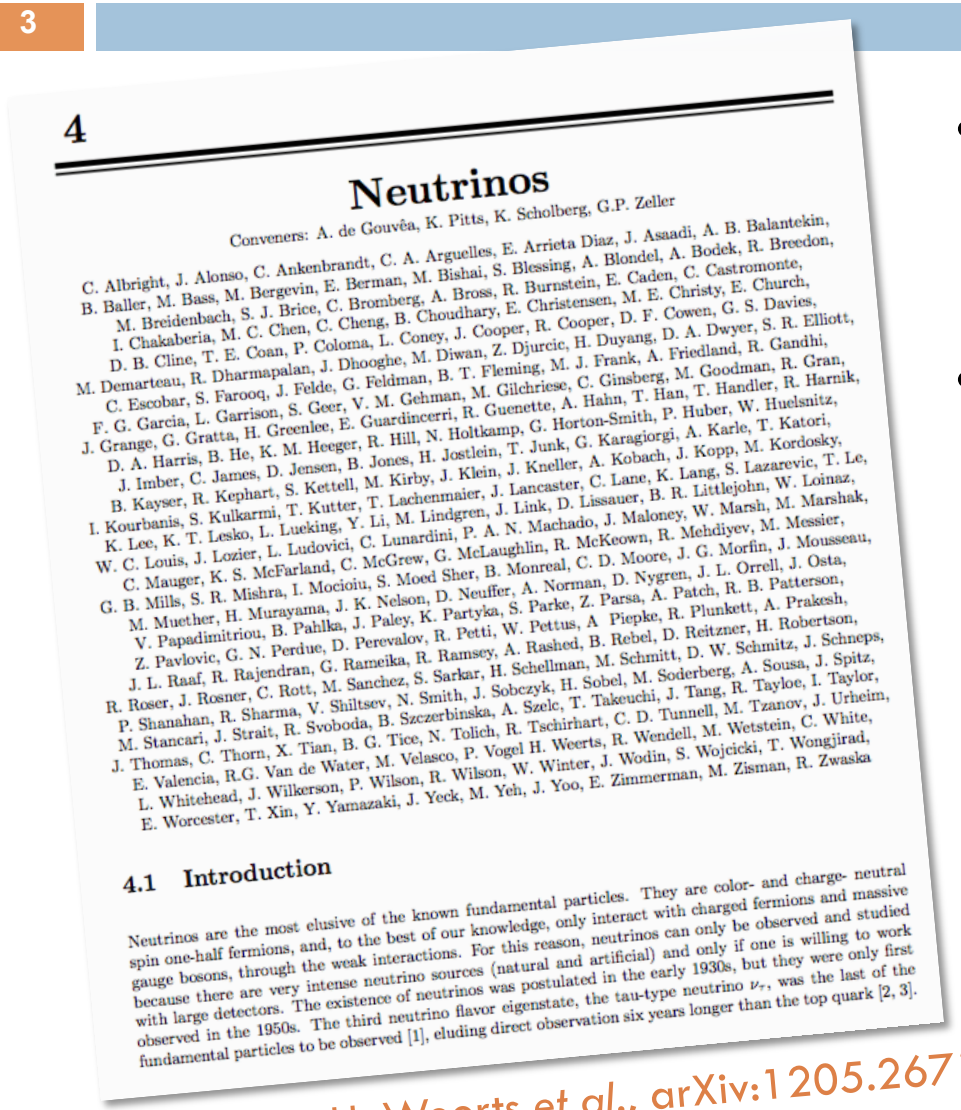
these are the questions that bug us and define our future direction – this is where we are headed

why are ν's so weird?

- is our picture correct or is there is new physics buried here?
  → need multiple experiments to nail down this physics

IF Report

- ν WG workshop on Oct 24, 2011 and IF meeting in Nov-Dec 2011



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Neutrinos

Conveners: A. de Gouvêa, K. Pitts, K. Scholberg, G.P. Zeller

C. Albright, J. Alonso, C. Ankenbrandt, C. A. Arguelles, E. Arrieta Diaz, J. Asaadi, A. B. Balantekin, B. Baller, M. Bass, M. Bergevin, E. Berman, M. Bishai, S. Blessing, A. Blondel, A. Bodek, R. Breedon, M. Breidenbach, S. J. Brice, C. Bromberg, A. Bross, R. Burnstein, E. Caden, C. Castromonte, I. Chakaberia, M. C. Chen, C. Cheng, B. Choudhary, E. Christensen, M. E. Christy, E. Church, D. B. Cline, T. E. Coan, P. Coloma, L. Coney, J. Cooper, R. Cooper, D. F. Cowen, G. S. Davies, M. Demarteau, R. Dharmapalan, J. Dhooghe, M. Diwan, Z. Djurcic, H. Duyang, D. A. Dwyer, S. R. Elliott, C. Escobar, S. Farooq, J. Felde, G. Feldman, B. T. Fleming, M. J. Frank, A. Friedland, R. Gandhi, F. G. Garcia, L. Garrison, S. Geer, V. M. Gehman, M. Gilchriese, C. Ginsberg, M. Goodman, R. Gran, J. Grange, G. Gratta, H. Greenlee, E. Guardincerri, R. Guenette, A. Hahn, T. Han, T. Handler, R. Harnik, D. A. Harris, B. He, K. M. Heeger, R. Hill, N. Holtkamp, G. Horton-Smith, P. Huber, W. Huelsnitz, J. Imber, C. James, D. Jensen, B. Jones, H. Jostlein, T. Junk, G. Karagiorgi, A. Karle, T. Katori, B. Kayser, R. Kephart, S. Kettell, M. Kirby, J. Klein, J. Kneller, A. Kobach, J. Kopp, M. Kordosky, I. Kourbanis, S. Kulkarni, T. Kutter, T. Lachenmaier, J. Lancaster, C. Lane, K. Lang, S. Lazarevic, T. Le, K. Lee, K. T. Lesko, L. Lueking, Y. Li, M. Lindgren, J. Link, D. Lissauer, B. R. Littlejohn, W. Loinaz, W. C. Louis, J. Lozier, L. Ludovici, C. Lunardini, P. A. N. Machado, J. Maloney, W. Marsh, M. Marshak, C. Mauger, K. S. McFarland, C. McGrew, G. McLaughlin, R. McKeown, R. Mehdiyev, M. Messier, G. B. Mills, S. R. Mishra, I. Mocioiu, S. Moed Sher, B. Monreal, C. D. Moore, J. G. Morfin, J. Mousseau, M. Muether, H. Murayama, J. K. Nelson, D. Neuffer, A. Norman, D. Nygren, J. L. Orrell, J. Osta, V. Papadimitriou, B. Pahlka, J. Paley, K. Partyka, S. Parke, Z. Parsa, A. Patch, R. B. Patterson, Z. Pavlovic, G. N. Perdue, D. Perevalov, R. Petti, W. Pettus, A Piepke, R. Plunkett, A. Prakesh, J. L. Raaf, R. Rajendran, G. Rameika, R. Ramsey, A. Rashed, B. Rebel, D. Reitzner, H. Robertson, R. Roser, J. Rosner, C. Rott, M. Sanchez, S. Sarkar, H. Schellman, M. Schmitt, D. W. Schmitz, J. Schneps, P. Shanahan, R. Sharma, V. Shiltsev, N. Smith, J. Sobczyk, H. Sobel, M. Soderberg, A. Sousa, J. Spitz, M. Stancari, J. Strait, R. Svoboda, B. Szczerbinska, A. Szelc, T. Takeuchi, J. Tang, R. Tayloe, I. Taylor, J. Thomas, C. Thorn, X. Tian, B. G. Tice, N. Tolich, R. Tschirhart, C. D. Tunnell, M. Tzanov, J. Urheim, E. Valencia, R.G. Van de Water, M. Velasco, P. Vogel H. Weerts, R. Wendell, M. Wetstein, C. White, L. Whitehead, J. Wilkerson, P. Wilson, R. Wilson, W. Winter, J. Wodin, S. Wojcicki, T. Wongjirad, E. Worcester, T. Xin, Y. Yamazaki, J. Yeck, M. Yeh, J. Yoo, E. Zimmerman, M. Zisman, R. Zwaska

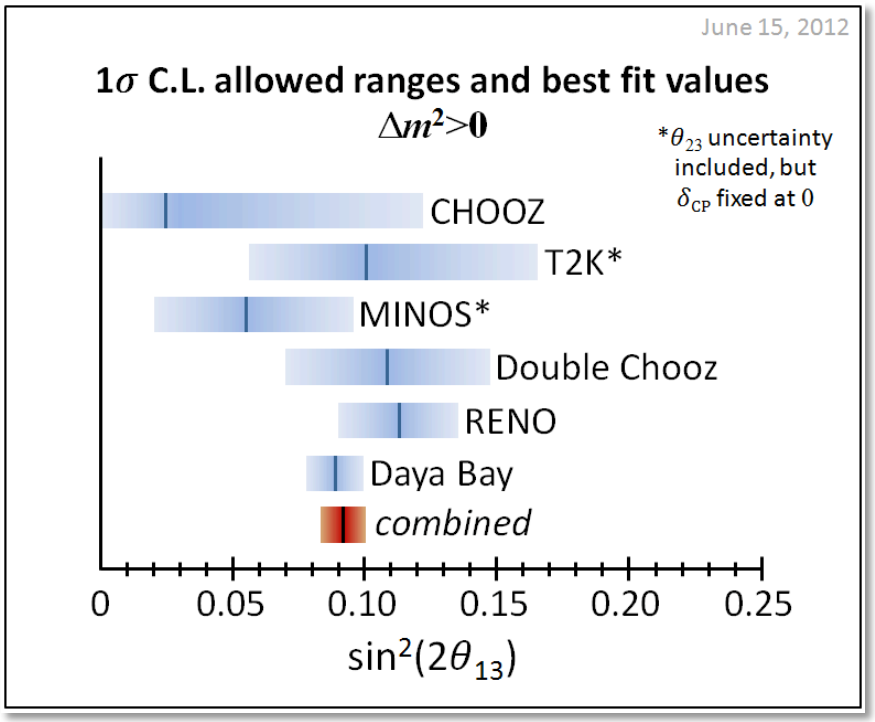
4.1 Introduction

Neutrinos are the most elusive of the known fundamental particles. They are color- and charge- neutral spin one-half fermions, and, to the best of our knowledge, only interact with charged fermions and massive gauge bosons, through the weak interactions. For this reason, neutrinos can only be observed and studied because there are very intense neutrino sources (natural and artificial) and only if one is willing to work with large detectors. The existence of neutrinos was postulated in the early 1930s, but they were only first observed in the 1950s. The third neutrino flavor eigenstate, the tau-type neutrino ν_τ, was the last of the fundamental particles to be observed [1], cluding direct observation six years longer than the top quark [2, 3].

J.L. Hewett, H. Weerts et al., arXiv:1205.2671

- neutrino chapter: 50+ pages
  - outlines state of the physics
  - lays out all of the opportunities
- <u>sections</u>:
  1. *testing the standard neutrino oscillation paradigm*
  2. *the nature of the neutrino (Majorana vs. Dirac)*
  3. *neutrino masses*
  4. *neutrino interactions*
  5. *anomalies and new physics*
  6. *synergy with other frontiers*
  7. *facilities*
- what's happened since then?

Smallest Mixing Angle



(R. Patterson)

- ***θ_{13} is non-zero!***

new!

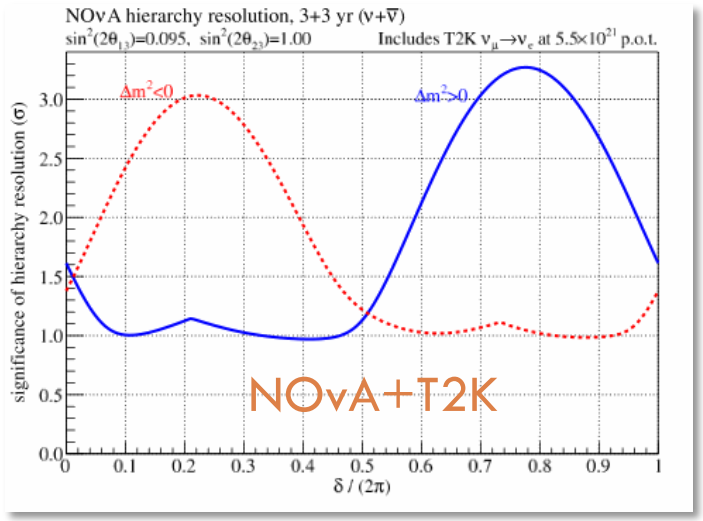
- large θ_{13} is great news for the field – it means we can get on to the business of searching for CP violation in the neutrino sector
- more precise θ_{13} measurements will help constrain models and allow us to better define the future program
- 2nd phase transition

Mass Hierarchy and CP Violation

- the two are closely coupled
- there are a number of ideas being discussed on how one can approach the issue of the neutrino mass hierarchy …

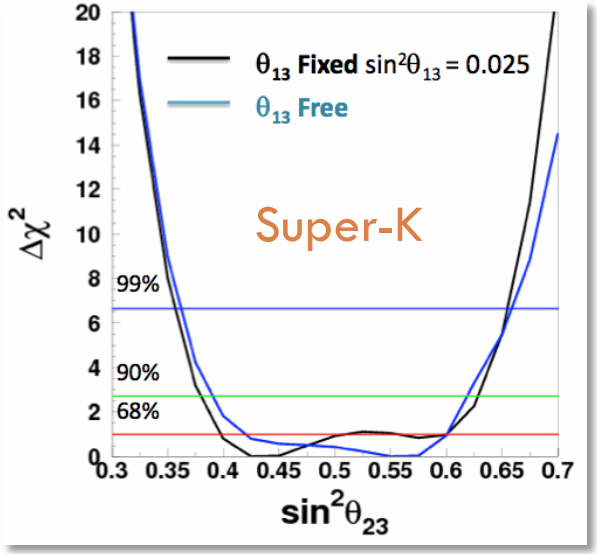
new!

accelerator-based ν's



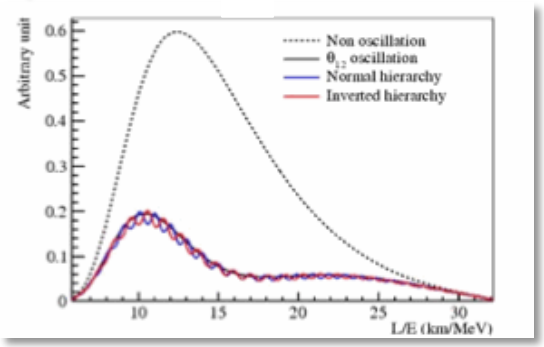
(+ LBNE, LBNO)

atmospheric ν's



(+ Hyper-K, INO, PINGU)

reactor ν's

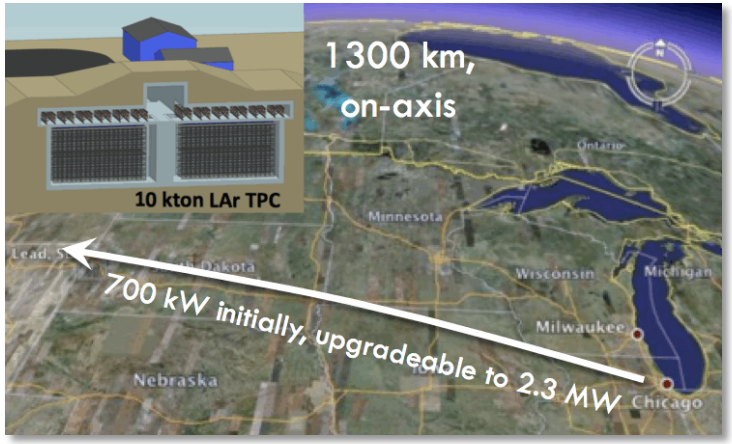


(Daya-Bay II)

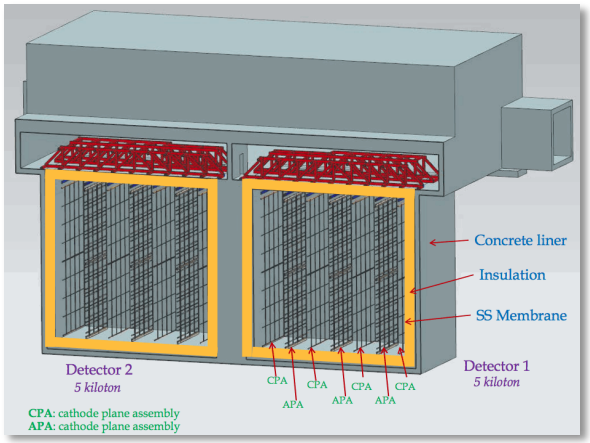
neutrino-less double beta decay

Long-Baseline Neutrinos

- to get at $\not{CP}$ in the ν sector, need a next-generation experiment: LBNE



- recognized as a high priority
- scientific opportunities here are great
- U.S. geography and accelerator/detector capabilities could not be better matched for this science
- have chosen a phased path forward for LBNE (community exercise; report in August 2012 – http://www.fnal.gov/directorate/lbne_reconfiguration)
  - 1st phase: 10 kton LAr at Homestake
  - CD-1 review at the end of this month



(1) Testing the Neutrino Paradigm

- this is the first time we've known all 3 mixing angles
- critical look at 3ν mixing from current fits to global data

(M.C. Gonzalez-Garcia *et al.*, arXiv:1209.3023)

- 15 years ago, not only hadn't measured any of this but didn't even know we could ask these questions!

	Free Fluxes + RSBL	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$

- so far, **the 3-flavor paradigm** appears to fit the data well *(modulo the SBL anomalies)*
- have a way to go *(have not done as good a job as has been done in the quark sector)*

- T2K, NOvA, MINOS+ ⟶ LBNE

(2) Anomalies: ν_S

- ***is the 3ν paradigm correct or are there more than the 3 "normal" neutrinos?***

  - there are hints that the ν sector may be more complex
    (LSND, MiniBooNE, Gallium, reactor flux, cosmology)


NEWSFOCUS

The Sterile Neutrino: Fertile Concept or Dead End?

Dozens of physicists gathered recently to debate whether the phantom particle exists and if it's worth hunting it

BLACKSBURG, VIRGINIA—Unlike old soldiers, some scientific concepts seem never to fade away. Take the hypothetical subatomic particle called the "sterile neutrino," which would be about the oddest bit of matter imaginable. For 15 years, researchers have accumulated hints from particle physics, nuclear physics, astrophysics, and cosmology that the particle—a more-elusive cousin of the nearly undetectable neutrinos—might be out there. But most physicists have found the evidence unconvincing, as most of the results pointing toward sterile neutrinos are of marginal statistical significance.

Recently, however, the case for sterile neutrinos has grown stronger, bolstered by a new analysis of data from nuclear reactors. So last month 60 physicists from around the world gathered here' to hash out the arguments for and against the existence of sterile neutrinos and to try to decide whether it's worth staging a dedicated experiment to settle the matter.

Performing such an experiment won't be easy. The hypothetical neutrinos are called sterile because they do not interact at all with known particles. "You're trying to prove the existence of something with no interactions," says Patrick Huber, a theorist here at Virginia Polytechnic Institute and State University (Virginia Tech). "It's like trying to prove the existence of God." Still, he says, it's time to figure out what it will take to discover or rule out sterile neutrinos once and for all. "I'm afraid we'll have the same workshop 15 years from now and will just have more [inconclusive] results that don't make the situation any clearer."

Some researchers say the case for a sterile neutrino is still half-baked. "I'm quite skepti-

Mystery machine. The guts of the LSND detector, which may have seen sterile neutrinos.

cal," says Yves Déclais, a neutrino physicist at the University of Lyon in France. "Each piece of evidence itself is not completely self-consistent," he says. "So I'm really concerned that there should be more work to understand each anomaly itself instead of trying to put together a dedicated experiment to look for sterile neutrinos."

Abundant in theory

Ordinary neutrinos are already weird. Nearly massless and hardly interacting with other matter, they are born in "weak" nuclear decays and interactions. For example, a neutron decays into a proton by emitting an electron and an antineutrino. A neutrino can emerge when a nucleus of the isotope beryllium-7 turns into lithium-7 by capturing an electron and releasing a neutrino. Trillions of neutrinos stream through each of us every second.

Weirder still, neutrinos come in three "flavors"—electron neutrinos, muon neutrinos, and tau neutrinos—that can morph into one another. For example, when cosmic rays strike the atmosphere, they create particles called muons that decay much as neutrons do, to produce muon neutrinos. The muon neutrinos can then "oscillate" or "mix" into other flavors before reaching Earth, as observed in 1998 by physicists using a giant subterranean detector called Super-Kamiokande in Japan. Electron neutrinos from the sun also change flavor, as physicists at the Sudbury Neutrino Observatory in Canada showed in 2001.

A sterile neutrino would be even more elusive than an ordinary neutrino. It would not participate in weak interactions and would arise only from ordinary neutrinos oscillating into a sterile form. As sterile neutrinos would not interact themselves, physicists could detect them only indirectly, by observing ordinary neutrinos disappearing or appearing where they are not expected.

Theorists have been thinking about sterile neutrinos since the late 1960s, when they first suspected that neutrinos from the sun oscillated. The morphing meant that neutrinos were not massless, and sterile neutrinos would help explain how the wispy particles put on weight.

Flavor-changing oscillations prove that neutrinos have mass because a massless particle must travel at light speed, and, according to Einstein's theory of relativity, at light speed time stands still, making change impossible. The standard model of particle

Online
sciencemag.org
Podcast interview with author Adrian Cho.

Downloaded from www.sciencemag.org on October 25, 2011

304 21 OCTOBER 2011 VOL 334 SCIENCE www.sciencemag.org

- a subset of the community has been thinking hard about this – important to figure this out

- sterile neutrino whitepaper (269 pages)
  K.N. Abazajian *et al.*, arXiv:1204.5379 [hep-ph], April 2012

new!

(2) Anomalies: ν_s

- quite a few ideas on how to test this

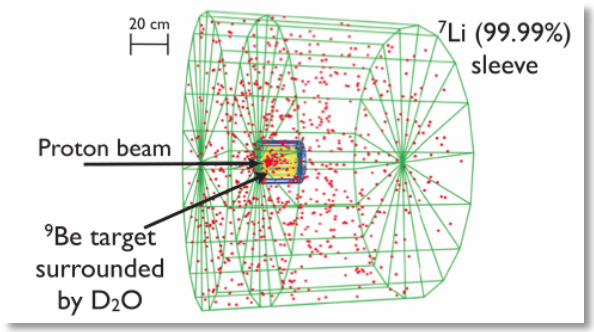
  (BooNE, bolometers, CERN LAr, IceCube, LAr1, MicroBooNE, MINOS disappearance, oscSNS, Planck, radioactive sources in reactor experiments, SCRAAM)

- plus, some new ones that have come out since the IF report:

new!

ISODAR

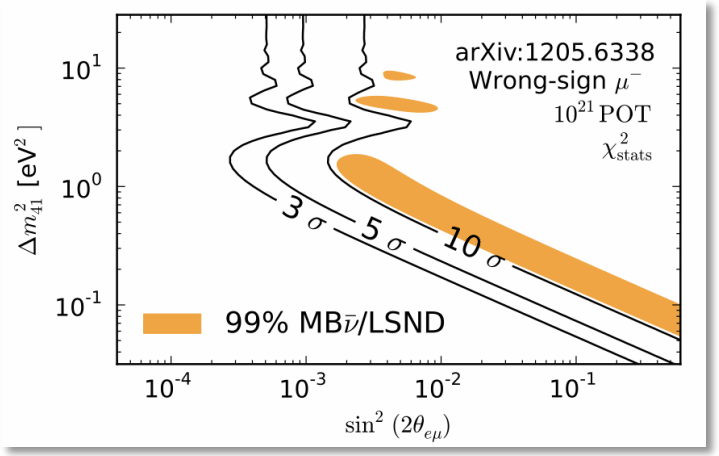
(A. Bungau et al., PRL 109, 141802, 2012)



νSTORM

ν workshop held at FNAL Sept 2012

(P. Kyberd et al., arXiv:1206.0294)



(2) Anomalies: ν velocity

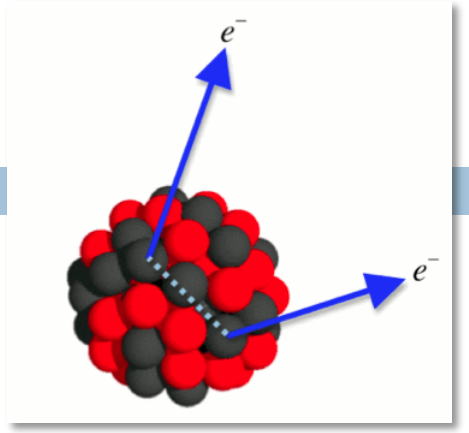
- ***do neutrinos travel faster than the speed of light?***

- All experiments at LNGS consistent with no measurable deviation from the speed of light for neutrinos (S. Bertlucci)
  - Borexino: $\delta t = 2.7 \pm 1.2$ (stat) $\pm$ 3(sys) ns
  - ICARUS: $\delta t = 5.1 \pm 1.1$(stat) $\pm$ 5.5(sys) ns
  - LVD: $\delta t = 2.9 \pm 0.6$(stat) $\pm$ 3(sys) ns
  - OPERA: $\delta t = 1.6 \pm 1.1$(stat) [+ 6.1, -3.7](sys) ns
- MINOS (P. Adamson)
  - Wrapped Spill:
  - $\delta = -11.4 \pm 11.2$ (stat) $\pm$ 29 (syst) ns
  - $v/c-1 = 0.5 \pm 1.3\times10^{-5}$ (68%)
  - Full Spill:
  - $\delta = -18 \pm 11$(stat) $\pm$ 29(syst)ns
  - $v/c-1 = 0.7 \pm 1.3\times10^{-5}$ 68%

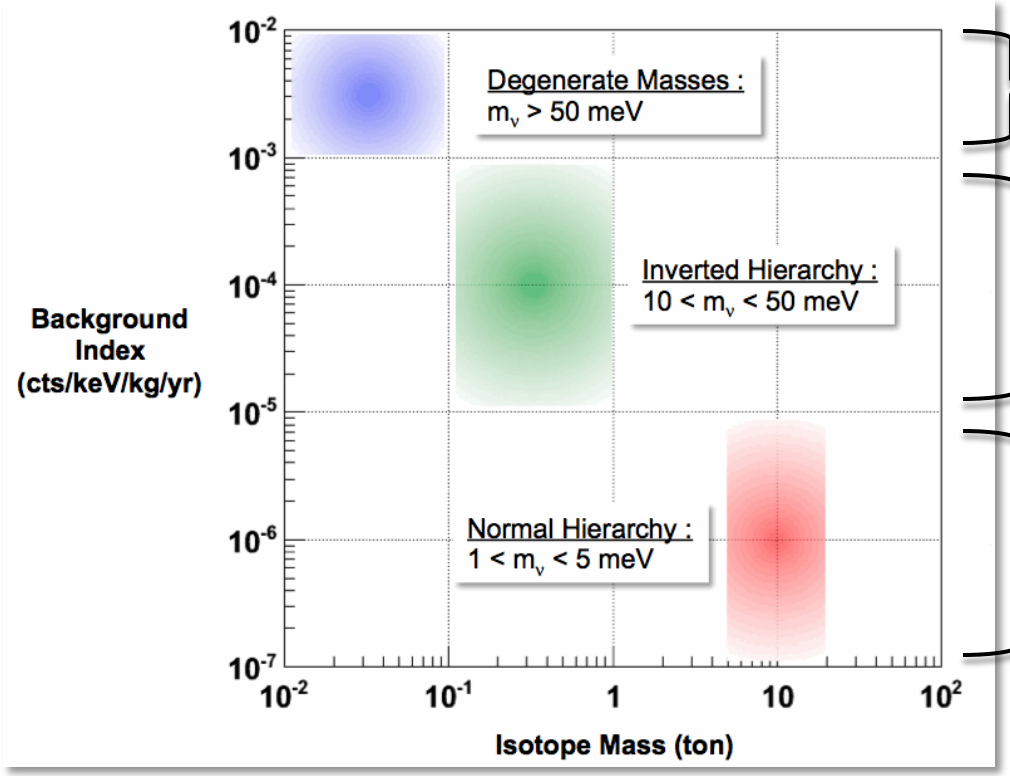
(K. Nishikawa, Neutrino 2012)

- the dust seems to be settling here and the answer appears to be no

(3) Nature of the Neutrino



- are neutrinos their own antiparticles?
- $0\nu\beta\beta$ only allowed if ν's are Majorana particles



we are here

next decade (bkgs, mass)

requires experimental breakthrus

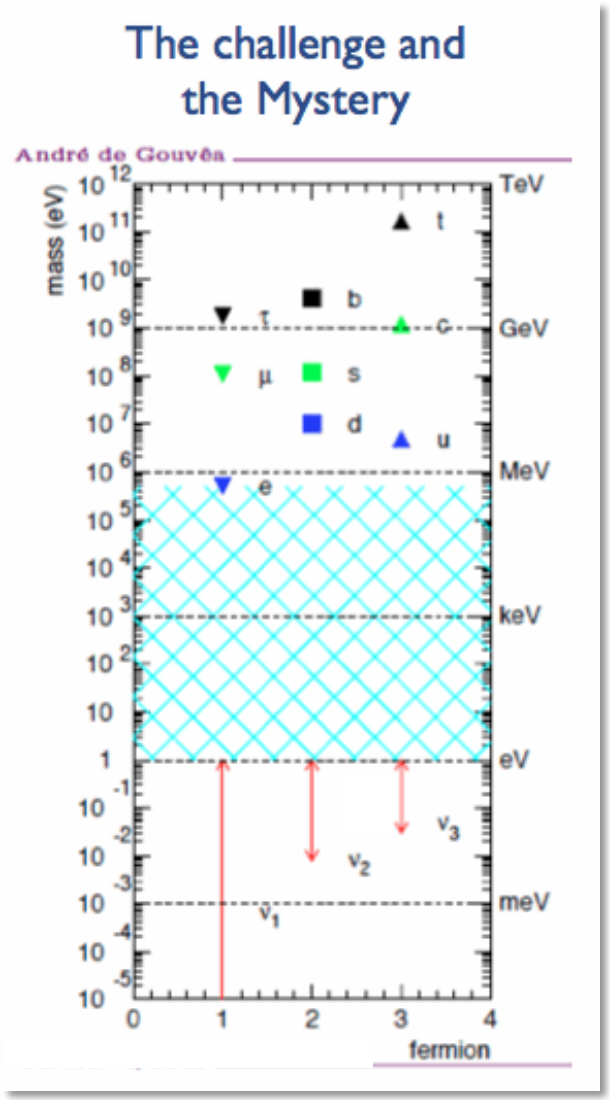
(D. Waters, NNN 2012)

- how do we best "pitch these efforts" in the context of the Snowmass process? (examples: $0\nu\beta\beta$, m_ν)

(4) Neutrino Masses

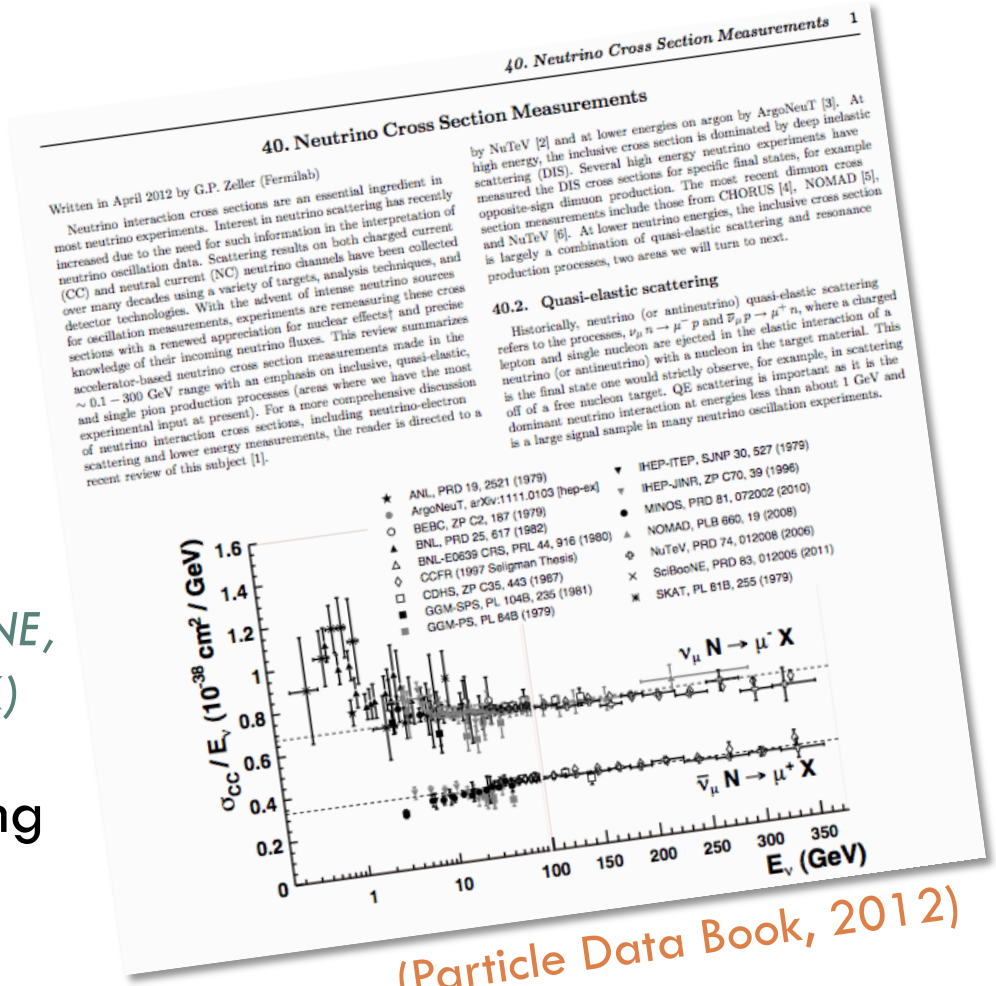
- tightest constraints from cosmology
  - *new Planck data coming soon*
- beta decay
  - *KATRIN will start taking data in 2015*
- other possible approaches being studied
  - *ECHO, MARE, Project-8*

no longer table top experiments!



(5) Neutrino Interactions

- must not forget that neutrino interactions are important in all of this
  - systematics will play an even larger role in future endeavors *(CP asymmetry smaller for large θ_{13})*
  - some surprises have been showing up in recent data
- new σ_ν measurements coming in *(ArgoNeuT, μBooNE, MINERνA, MiniBooNE, MINOS, NOMAD, NOvA, SciBooNE, T2K)*
- new ideas for the future addressing ν_e & $\overline{\nu}_e$ cross sections! *(νSTORM)*



(Particle Data Book, 2012)

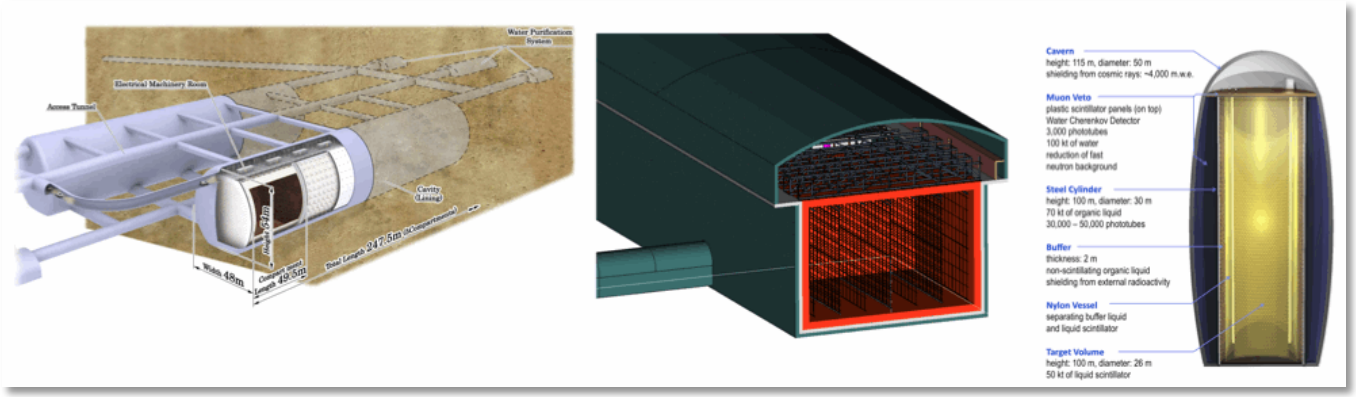
(6) Synergies

- in the IF report, we highlighted connections between neutrinos and other areas *(other IF sub-groups and with other frontiers)*

- always more work to do to identify areas of overlap between neutrinos and other areas

(7) Facilities & Detectors

- **facilities**
  - *Project-X*
  - *also, cyclotrons and muon storage rings*
- **technologies for next-generation detectors**



Water Cerenkov *Liquid Argon TPCs* *Liquid Scintillator*

- unique physics potential & technological advancements have produced a fertile environment new ideas

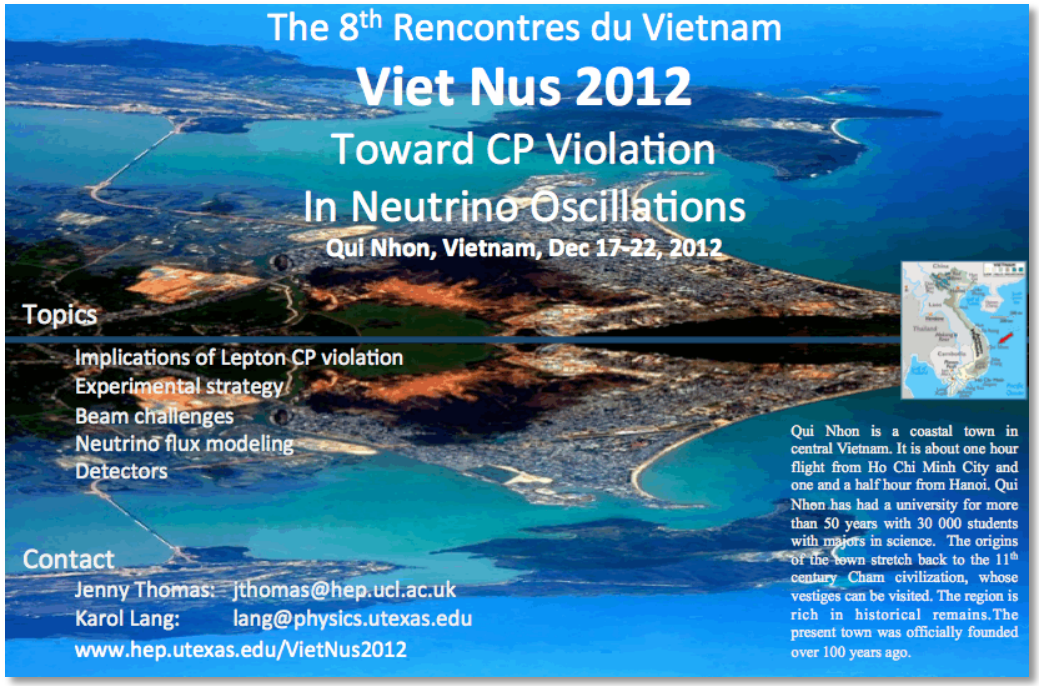
- a lot of clever people thinking of ways to approach the remaining questions in neutrino physics

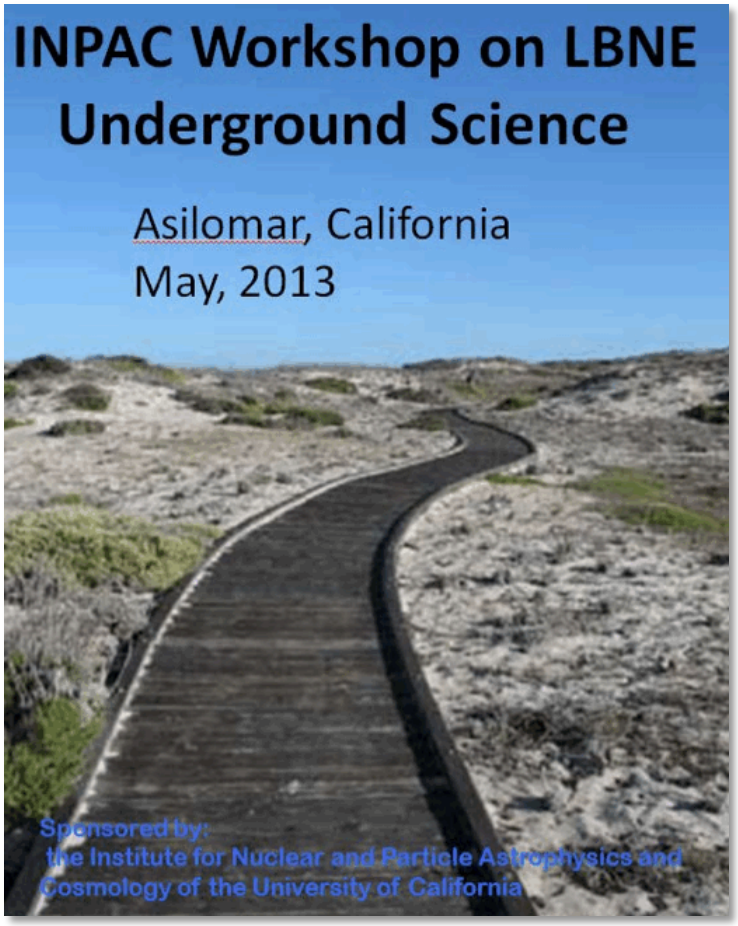
Plans Leading Up To Next Summer

- What's next?
- **additional input is welcome!**
  (please send to Andre, Kate, Sam, Kevin)
  - "whitepapers" that we received before Rockville were incredibly helpful *(few-page summaries)*
  - please send and specify which "tier" your idea corresponds to: *small, medium, large*
  - will update IF neutrino document and distill into a shorter summary *(if needed)*
- an interim **face-to-face neutrino WG meeting** before summer 2013
  - one suggestion: piggyback on DURA meeting at SLAC in March?

Opportunities for Input

- between now and Snowmass …





- also, NSAC (Nuclear Sciences Advisory Committee) report in January 2013

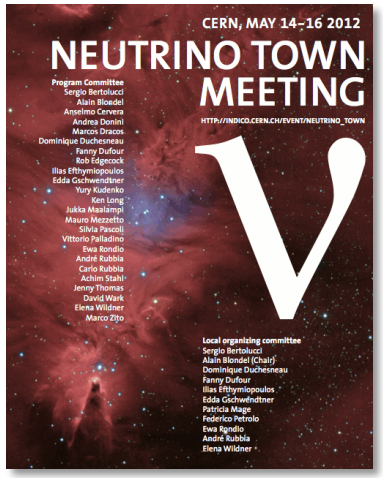
Neutrinos Worldwide

- **SNOLAB**- SNO+, EXO, Halo
- **China -** Daya Bay II
- **India** - INO

U.S. is involved in many of these!

- **Japan**
  - Report on Future Projects of High Energy Physics, Feb 2012
    http://www.jahep.org/office/doc/201202_hecsubc_report.pdf
  - KEK roadmap expected to come out in March 2013

- **Europe**
  - EOI for LBNO submitted to CERN, June 2012
    http://cdsweb.cern.ch/record/1457543
  - European Strategy meeting, *Sept 2012 in Krakow*
  - updated strategy to be presented to CERN council March 2013



Conclusions

- we know that significant discoveries are possible in neutrino physics
  - *large θ_{13} has enabled the path to CP violation in the ν sector*
  - *answers to the questions of the ν mass ordering, the nature of the ν, and absolute ν masses are within our reach*
- there are many opportunities in front of us … this is very exciting!
- we have a plan - we have experiments running now/soon and solid ideas beyond that – we need to articulate this coherently
- please send us your input!

Neutrino WG Email List

- if you are not already on the neutrino WG email list and would like to be, please send an email to Andre, Kate, Kevin, and/or Sam to get added